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Abstract: The ice flow path and dynamic behaviour of the British-Irish Ice Sheet has been subject to renewed interest and controversy in recent years. Early studies in eastern England argued for interaction with Fennoscandian ice onshore in Britain, instigating re-examination of the sedimentology and provenance of many Pleistocene till successions. These studies instead supported an exclusively British provenance, and are used to predict southward advance of a broadly coast-parallel North Sea Lobe. Quantitative lithological and palynological analysis of the Pleistocene till succession in Holderness, East Yorkshire, however, remains to be carried out. We examined the lithologically diverse Skipsea Till in order to reconstruct ice flow pathways to the Holderness coast during the Pleistocene, thereby constraining which areas of substrate were subglacially eroded and entrained prior to deposition. The till yields a diverse range of soft, low-durability and uniquely British allochthonous material, including Permian Magnesian Limestone, Carboniferous limestone and coal, and Carboniferous pollen and spore assemblages that would be unlikely to survive polyphase reworking. Ice extended southwards through southern Scotland, incorporating material in north ease England, north-east Yorkshire and the western margin of the North Sea Basin (NSB), supporting a recurrent ice flow pathway for the eastern margin of the British-Irish Ice Sheet during the Mid to Late Pleistocene.

Pleistocene till provenance in east Yorkshire: reconstructing ice flow of the British North Sea Lobe

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Abstract

The ice flow path and dynamic behaviour of the British-Irish Ice Sheet has been subject to renewed interest and controversy in recent years. Early studies in eastern England argued for interaction with Fennoscandian ice onshore in Britain, instigating re-examination of the sedimentology and provenance of many Pleistocene till successions. These studies instead supported an exclusively British provenance, and are used to predict southward advance of a broadly coast-parallel North Sea Lobe. Quantitative lithological and palynological analysis of the Pleistocene till succession in Holderness, East Yorkshire, however, remains to be carried out. We examined the lithologically diverse Skipsea Till in order to reconstruct ice flow pathways to the Holderness coast during the Pleistocene, thereby constraining which areas of substrate were subglacially eroded and entrained prior to deposition. The till yields a diverse range of soft, low-durability and uniquely British allochthonous material, including Permian Magnesian Limestone, Carboniferous limestone and coal, and Carboniferous pollen and spore assemblages that would be unlikely to survive polyphase reworking. Ice extended southwards through southern Scotland, incorporating material in north ease England, north-east Yorkshire and the western margin of the North Sea Basin (NSB), supporting a recurrent ice flow pathway for the eastern margin of the British-Irish Ice Sheet during the Mid to Late Pleistocene.

1. Introduction

Pleistocene glacial deposits and landforms along the eastern English coast are integral to deciphering the dynamics and extent of the North Sea Lobe during expansion and retreat of the last British-Irish Ice Sheet (BIIS). Onshore advance of the North Sea Lobe has been demonstrated to occur during several different Mid and Late Pleistocene glaciations in County Durham, north Yorkshire and north Norfolk based upon detailed provenance analysis (Lee et al., 2002; Davies et al., 2009, 2011, 2012; Roberts et al., 2013). Although subject to recent geochemical, sedimentological and palaeontological assessment (Boston et al., 2010; Evans & Thomson, 2010; Bateman et al., 2011), the Marine Isotope Stage (MIS) 2 stratotype on the Holderness coast, east Yorkshire, is yet to yield systematic and quantitative erratic clast and palynomorph provenance data. Holderness is of particular importance given its chronostratigraphical significance, with Late Pleistocene glacial deposits overlying *in situ* organic-rich silts (the 'Dimlington Silts') which yield radiocarbon dates of 22.4-21.3 cal. ^{14}C ka BP (18.25±0.25 ka BP) and 23.3-21.2 cal. ^{14}C ka BP (18.5±0.4ka BP) (Catt & Penny, 1966; Penny et al., 1969), constraining the earliest possible age for ice advance into this region during the Late Devensian.

A lithostratigraphy for the Holderness coast has long been established (Catt & Penny, 1966; Madgett & Catt, 1978; Bowen, 1999; Catt, 2007). However, recent studies focussing on the 3D geometry and geochemical composition of the major till units have raised significant questions regarding their regional correlation (Boston et al., 2010; Evans & Thomson, 2010). Reliable chronostratigraphical and lithological provenance constraints are therefore critical to assess the significance of these units in the wider context of BIIS behaviour. In this study, we examine the composition and provenance of the Skipsea Till which is commonly associated with the first Late Devensian advance of North Sea ice into the region. This is to help reconstruct: (1) the flow path of the North Sea ice lobe; (2) identify areas of substrate that were being subglacially eroded and entrained.

2. Pleistocene deposits of the Holderness coast

The Pleistocene lithostratigraphy in Holderness has traditionally been subdivided into three till members based principally upon lithological properties including colour, particle size distribution, clast (qualitative) and heavy mineral composition, and matrix calcium carbonate percentage (Catt & Penny, 1966; Madgett & Catt, 1978; Bowen, 1999; Catt, 2007). These are termed the Basement Till, Skipsea Till and Withernsea Till members, and are separated by, and in places inter-bedded with, stratified silts and sands (Catt, 2007). The lowermost Basement Till rests on the underlying Cretaceous Chalk bedrock (Catt & Digby, 1988; Catt, 2007), and depending on its stratigraphical relationship to the Ipswichian Sewerby Raised Beach is either pre-Ipswichian (Catt & Penny, 1966; Penny & Catt, 1967; Bateman & Catt, 1996; Catt, 2001, 2007) or Devensian in age (Eyles et al., 1994; Boston et al., 2010; Evans & Thomson, 2010). At Dimlington, the stratotype for these glacial deposits, the Basement Till is overlain by the Dimlington Silts (~18.5-18.2 ka) (Penny et al., 1969), and in turn by the Skipsea and Withernsea tills (Rose, 1985; Evans & Thomson, 2010). Recent Optically Stimulated Luminescence (OSL) age determinations of deposits between the Skipsea and Withernsea Tills constrain the timing of initial advance (Skipsea Till) to ~21.7-16.2 ka, with a second oscillation of the North Sea Lobe, and deposition of the Withernsea Till, occurring between 16.2 ka and terminal retreat at ~15.5 ka (Bateman et al., 2011).

Between Withernsea and Bridlington the layer-cake lithostratigraphical arrangement of the major till units identified by Catt & Penny (1966) further to the south at Dimlington is less discernible. Evans & Thomson (2010) have argued that the till sequence here is glacitectonically-deformed and thrust-thickened with deformation produced by a south to south-eastwards advance of the North Sea ice lobe. Equally it is evident that the intra-till variability is typically greater than the inter-till variability (Boston et al., 2010), and this is especially applicable to the Skipsea Till (Catt, 2007). Recent unpublished studies recognise potentially five distinct facies of Skipsea Till between Withernsea and Barmston based upon matrix colour, matrix texture and clast content (British Geological Survey, unpublished data). These include: (a) Chalk-rich facies as previously defined at Dimlington by Catt & Penny (1966); (b) local Quaternary-rich facies; (c) Mercia Mudstone-rich facies; (d) Kimmeridge Clay-rich facies; and (e) Lias-rich facies.

Various studies have debated the provenance of the Skipsea Till, with some authors advocating west-east ice dispersal from the Lake District (Bisat, 1939; Foster, 1987), whilst others favour erratic transport from northern Britain (Catt & Penny, 1966; Madgett & Catt, 1978; Catt, 2007). Whilst recent re-examination of deposits considered correlative in north Yorkshire (Roberts et al., 2013), County Durham (Davies et al., 2009) and the North Sea Basin (Davies et al., 2011) yield a predominantly northern British signature, quantitative analysis of the clast lithology and palynomorph content of the Skipsea Till (and other distinctive till units) in Holderness remains to be carried out. Previous quantitative studies of the Skipsea Till have focussed upon the application of heavy mineralogy (Madgett and Catt, 1978) and geochemistry (Boston et al., 2010) to differentiate between different till units within the region rather than reconstruct till provenance. This study represents the initial findings of a major study examining the lithological and provenance variations within the Skipsea Till. The focus of this paper is to examine the clast and micro-fossil provenance from the chalk-rich facies (A) of the Skipsea Till. This will facilitate comparison with other erratic transport paths identified for the eastern British-Irish Ice Sheet, and thus contribute to our understanding of the ice dispersal patterns which fed southwards advance of the North Sea Lobe.

3. Methods

Multiple bulk samples of Skipsea Till (Facies E) were collected for the extraction of erratic clast and palynomorph assemblages from the base of coastal cliff sections at Easington (National Grid Reference TA 406 190), southern Holderness (Fig. 1). The sample site is situated 3 km to the south-southeast of the stratotype sections at Dimlington with the chalk-rich facies of the Skipsea Till being readily correlatable between the two based upon bulk lithology and stratigraphical position. The unit sampled is a dark grey-brown (Munsell Colour: 5Y 3/1) matrix-supported diamicton, with sub-angular to sub-rounded clast morphologies alongside sparse glacially striated forms (Fig. 2). Samples were obtained from a single section, with sampling restricted to freshly cleaned faces to minimise the effects of weathering and surficial re-working, and thus ensure analysis of *in situ* material.

Erratic clasts were extracted by disaggregating bulk samples of the till in sodium hexametaphosphate [$(NaPO_3)_6$] and wet-sieving through 16 mm, 8 mm, 4 mm and 2 mm sieves. The 8-16 mm and >16 mm size fractions were categorised in terms of lithology and stratigraphical age, and hence regions of likely provenance through correlation with reported outcrop occurrences. The allochthonous palynomorph content was extracted from two 50 g sub-samples of the bulk material through non-acid palynological preparation techniques (Riding & Kyffin-Hughes, 2004, 2006). Three slide fractions were prepared from each residue through swirling and heavy liquid separation (Riding & Kyffin-Hughes, 2004), representing a light, heavy and centrifuged sub-sample. The palynomorphs were grouped according to stratigraphical ranges, thus indicating their likely provenance.

4. Results

4.1. Clast Lithological Analysis

The total 8-16 mm and >16 mm erratic population of the Skipsea Till (Facies E) comprises a diverse suite of locally-derived sedimentary lithologies (76.85%), alongside subsidiary far-travelled sedimentary (4.18%) and crystalline components (13.53%) (Table 1, Fig. 3). The remaining clasts (5.86%) represent erratic lithologies of indeterminate provenance, including quartzo-feldspathic sandstone, fine-grained olive-green mudstone and intermediate igneous lithologies, whose characteristics were not sufficiently diagnostic to discern a stratigraphical association.

Clast lithologies derived from Pleistocene successions include reworked white-brown (weathered) flint, Greensand chert and sandstone, and impure quartzite pebbles, constituting 10.32% of the sample population (Fig. 3). Cretaceous sedimentary lithologies are most abundant (30.68%), consisting of chalk and black-grey (unweathered) flint (Table 1). The Jurassic assemblage (9.76%) consists of calcareous sandstone, silty micaceous limestone and micaceous mudstone, alongside clasts of black bituminous mudstone (the Mulgrave Shale Member of the Whitby Mudstone Formation or "Jet Rock"), ironstone, oolitic and/or shelly limestone and allochthonous shell fragments. The Permo-Triassic fraction (12.83%) is dominated by Magnesian Limestone, crystalline dolostone and dolomitic sandstone, with subordinate quantities of brick-red Sherwood Sandstone, evaporite-bearing sandstone and limestone, gypsum, and wind-faceted sandstone (*dreikanter*). Carboniferous erratic lithologies (13.39%) include organic-rich sandstone, dark grey-brown and pink-red (haematite stained) crystalline limestone, and single occurrences of coal and fossil material. The remaining sedimentary constituent comprises minor, yet persistent populations of Devonian 'Old Red Sandstone' (1.95%) and Lower Palaeozoic greywacke and dark green chert (2.23%).

Within the crystalline component (Table 1, Fig. 3), Devonian lithologies dominate (8.65%), and include rhyolitic and andesitic porphyries, felsic intrusive material, and subsidiary quantities of felsite, non-porphyritic andesite, volcaniclastic rock and quartzose metamorphic lithologies. The Carboniferous fraction (4.18%) is dominated by mafic igneous lithologies, alongside trace quantities of intermediate trachytic lava. Permian crystalline lithologies

(0.28%) are restricted to single occurrences of rhomb porphyry, and an unknown microgranite.

4.2. Palynological Analysis

Facies E of the Skipsea Till contains a diverse association of allochthonous Carboniferous, Jurassic, Cretaceous and Quaternary palynomorphs, in addition to abundant non-age diagnostic forms (Table 2; Riding, 2012). Carboniferous spores predominate (51.84%), including large populations of *Densosporites* spp. and *Lycospora pusilla*, alongside more minor occurrences of *Cirratriradites saturni*, *Radiizonates* spp., *Reticulatisporites* spp., *Endosporites globiformis*, *Simzonotriletes intortus* and *Tripartites vetustus* (Fig. 4). With the exception of the latter, indicative of Late Mississippian (Viséan to Early Bashkirian) input (Riding, 2012), the assemblage is characteristic of the Pennsylvanian (Late Bashkirian to Kasimovian). Jurassic palynomorphs constitute 12.78% of the population (Table 2), including pollen and spores, and rare dinoflagellate cysts. Dinoflagellate cyst taxa recognised include the Late Sinemurian marker *Liasidium variabile*, the characteristically Early Toarcian *Nannoceratopsis deflandrei* subsp. *senex* and the Callovian to Middle Oxfordian index *Gonyaulacysta jurassica* subsp. *adecta*, in addition to forms from the Kimmeridgian to Tithonian such as *Oligosphaeridium patulum*, *Perisseiasphaeridium panosum* and *Systematophora* spp. The Jurassic pollen assemblage contains the characteristically Early and Mid Jurassic genus *Chasmatosporites*, and *Callialasporites* spp. which is typical of the Mid and Late Jurassic, alongside minor occurrences of characteristically Jurassic spores such as *Ischyosporites variegatus* (Riding, 2012).

The age-diagnostic palynomorph population with the lowest abundance are Cretaceous palynomorphs (1.23%), with dinoflagellate cysts recognised including *Cribroperidiium* spp., *Odontochitina operculata*, *Hystrichodinium voigtii* and ?*Isabelidinium* sp. With the exception of the latter Late Cretaceous form, this assemblage is characteristic of the Early Cretaceous (Riding, 2012). These occur alongside spores of the genus *Cicatricosisporites*, which is typically Early Cretaceous. Palynomorphs derived from Quaternary deposits were found to be low in abundance (6.65%); these include *Pediastrum* spp., *Spiniferites* spp and *Tilia* (Table 2). The remaining palynomorph population (27.50%) consists of long-ranging, and thus non-age diagnostic forms such as acanthomorph acritarchs, bisaccate pollen and smooth fern spores.

5. Discussion

5.1. Provenance of the erratic clast and palynomorph assemblages

The chalk-rich facies of Skipsea Till (Facies A) at Easington contains a diverse assemblage of locally-derived and far-travelled erratic clasts and palynomorphs, incorporated through erosion and entrainment of sedimentary and igneous strata in northern England, southern Scotland and the western margin of the North Sea Basin (Fig. 5). The wide geological range of lithologies present suggests that many of the major sedimentary bedrock units in eastern England were not extensively buried beneath superficial deposits and thus were actively eroded and being entrained subglacially.

Jurassic, Cretaceous and Quaternary sedimentary lithologies are considered to be locally derived from the Cleveland Basin, southern Yorkshire, and adjacent offshore strata. These include chalk and grey-black (fresh) flint from the Upper Cretaceous chalk bedrock (Kent, 1980; Cameron et al., 1992), immediately underlying the Pleistocene succession in Holderness (Catt, 2007). Their local derivation, and hence minimal erosion during transport, is consistent with the limited occurrence of Cretaceous spores and dinoflagellate cysts. Lower Jurassic material, typical of the Cleveland Basin, include *Liasidium variabile* and *Nannoceratopsis deflandrei* subsp. *senex* derived from the Redcar Mudstone and Whitby Mudstone formations, respectively (Brittain et al., 2010; Bucefalo Palliani & Riding, 2000), alongside trace quantities of the Mulgrave Shale Member ("Jet Rock"), which is unique to Yorkshire. Oolitic and/or shelly limestones and allochthonous shell fragments are more characteristic of the Mid to Late Jurassic strata of the northern Cleveland Basin (Fig. 5), consistent with the occurrence of *Gonyaulacysta jurassica* subsp. *adecta* (see Riding & Thomas, 1997), which was likely to have been eroded from the Callovian-Oxfordian Osgodby Formation to Coralline Oolite Formation succession. White and brown (weathered) flint and well rounded quartzite pebbles were provenanced to the locally widespread Pliocene and Pleistocene deposits, both on- and offshore (Lee et al., 2002). Trace quantities of Cretaceous Greensand chert and glauconitic sandstone are likewise considered to be derived through reworking within Quaternary deposits due to their lack of outcrop exposure north of Holderness (Cameron et al., 1992; Mitchell, 1995; Hopson et al., 2008).

More far-travelled sedimentary lithologies include the Permian-Triassic Sherwood Sandstone Group and Magnesian Limestone Formation, both of which outcrop extensively across northern Yorkshire, southern County Durham and offshore (Fig. 5). Incorporation of abundant Carboniferous material, including organic-rich sandstones and limestones, alongside single occurrences of coal and thermally-matured coral, indicates derivation from County Durham and Northumberland or the immediately adjacent offshore area, as Carboniferous strata do not outcrop in the central North Sea (Cameron et al., 1992). Coal material could arguably be derived from Jurassic strata in Yorkshire and the adjacent offshore, but the greater outcrop occurrence of Carboniferous coal and the abundance of Pennsylvanian ‘Coal Measures’ palynoflora provides strong support for a Carboniferous age. Pink-purple stained limestones of the Upper Coal Measures are considered more typical of the Midland Valley strata, given their restricted extent in north-east England. Overall, however, the low durability and large population of Carboniferous sedimentary lithologies support a more proximal principal source region.

Rare far-travelled sedimentary clasts include lower Palaeozoic greywacke likely to have been derived from the Southern Uplands (Greig, 1971), having only limited exposure in north-east England (Taylor et al., 1971), alongside Devonian Old Red Sandstone clasts of southern Scottish provenance (Greig, 1971; Cameron & Stephenson, 1985). In addition, crystalline metamorphic lithologies characteristic of the Scottish Grampian Highlands (Johnstone, 1966) are extremely low in abundance. Alternatively, theses erratics may be reworked clasts from the widespread Dalradian-rich Old Red Sandstone conglomerates of the Midland Valley (Cameron & Stephenson, 1985).

The far-travelled component is dominated by igneous lithologies typical of the Devonian Cheviot Volcanic Complex (Fig. 5). These include characteristic purple to red-brown rhyolitic and green to dark brown andesitic lavas and porphyries, alongside abundant intrusive lithologies eroded from the main granitic pluton (Greig, 1971; Taylor et al., 1971; Robson, 1980). This is established as the principal source of felsic intrusive material due to its large extent and abundance of associated Cheviot lavas within the till. This is in contrast to the paucity of erratic material derived from other major volcanic provinces, such as the Lake District and the Grampian Highlands (Johnstone, 1966; Taylor et al., 1971). Basaltic erratic lithologies may be provenanced to the extensive Carboniferous and Devonian lava successions of north-east England (Taylor et al., 1971), and particularly southern and central Scotland (Greig, 1971; Cameron & Stephenson, 1985). Quartz-dolerite erratics were likely to have been incorporated through the erosion of mafic intrusions in northern Britain, including the widespread Tertiary dyke swarm (Emeleus & Gyopari, 1992). However, the abundance of Carboniferous sedimentary lithologies, and entrained erratics from the proximal Cheviot volcanic complex provides support for derivation from the prominent Carboniferous Whin Sill in northern England, and potentially from the coeval Midland Valley Sill in central Scotland (Taylor et al., 1971; Dunham & Strasser-King, 1982; Bateson & Johnson, 1984; Cameron & Stephenson, 1985). The single occurrence of volcaniclastic material within the sample is considered to have been derived from the Devonian Ochil Hills Formation in the Midland Valley (Cameron & Stephenson, 1985). The absence of extrusive volcanic lithologies characteristic of north-west England, e.g. the fine-grained, pyroclastic material and green-blue to grey andesitic lavas of the Borrowdale Volcanic District (Taylor et al., 1971), negates its inclusion as an erratic source region.

Only two clasts of probable Scandinavian provenance were recorded within the Skipsea Till (Facies E), consisting of rhomb porphyry and an unknown microgranite. Possible correlatives of the latter include the pyterlite variety of Rapakivi granite (Müller, 2007), sourced from the Baltic sector of the Fennoscandian Shield (Fig. 5), or a microcrystalline form of the Norwegian Drammensgranit (Lee et al., 2006). The latter may be more consistent with the Oslofjord derivation of the rhomb porphyry erratic (Neumann et al., 2004; Larsen et al., 2008), although the granite clast is not a common constituent of Norwegian erratic assemblages recognised elsewhere (Ehlers, 2011 pers. comm). The rare occurrence of these clasts and the common occurrence of low-durability lithologies that are unique to eastern England suggests that the Scandinavian erratics were reworked from pre-existing deposits situated in the current offshore by the BIIS as opposed to direct derivation by Fennoscandian ice (*sensu* Hoare & Connell, 2005; Lee et al., 2005). Possible sources include ice-rafted erratics from Early Pleistocene coastal deposits (cf. Larkin et al., 2011; Hoare, 2012), or from the reworking of older or contemporary deposits with reported Scandinavian input e.g. the Basement Till on the Holderness coast (Catt, 2007) or the Fisher Formation offshore (Davies et al., 2011).

Incorporation of some of the British lithologies through reworking of older glacigenic or non-glacigenic strata is likely – especially robust and durable clast lithologies such as Greensand chert, flint (white, brown and chatter-marked), vein quartz and quartzite. However, the abundant occurrences of soft, non-durable sedimentary lithologies, including Jurassic limestone, mudstone and the Mulgrave Shale Member (“Jet Rock”), Permian Magnesian

Limestone and Carboniferous limestone and coal, would be unlikely to have survived multiple episodes of reworking, particularly in light of the evidence for highly-abrasive subglacial conditions (e.g. striated clasts) (Lee et al., 2002). Similarly, during repeated recycling, the Carboniferous palynomorph assemblage would likely have become numerically diluted (e.g. Riding et al., 1997), rather than constituting approximately 52% of the assemblage (Table 2), and would be unlikely to have preserved the abundant intact palynomorphs (e.g. Fig. 4). The relative abundance of non-local erratic materials (e.g. crystalline and sedimentary lithologies) and their grouping and attribution to specific stratigraphical and geographical sources suggests that this component of the clast assemblage is also of primary origin.

5.2. Erratic transport paths of the North Sea Lobe

The distinctive suite of lithologies and palynomorphs within Facies A of the Skipsea Till at Easington supports transport of material sourced from ice dispersal centres situated over the Midland Valley and southern central Scotland that fed into the Southern Uplands, and then extended southwards entraining crystalline lithologies from the Cheviot Hills, and successive Palaeozoic and Mesozoic strata along the east coast of England (see Fig. 6). This flow trajectory is consistent with a range of Mid and Late Pleistocene tills in eastern England attributed to derivation from the North Sea Lobe of the BIIS during several different Mid and Late Pleistocene glaciations (e.g. Lee et al., 2002; Boston et al., 2010; Davies et al., 2012; Roberts et al., 2013). Although these tills consistently record input from northern Britain along a broadly southerly trajectory, the influence and activity of different ice dispersal centres within the BIIS is variable.

Re-examination of Middle Pleistocene tills in County Durham (Davies et al., 2012) and north Norfolk (Lee et al., 2002) reveals a broad suite of diagnostically British clast lithologies and palynomorphs, rejecting earlier predictions of a Scandinavian provenance in these units (Trechmann, 1915, 1931; Boswell, 1916; Bridge & Hopson, 1985; Ehlers et al., 1991). Rare Scandinavian erratics, where present, are therefore considered to reflect reworking within the North Sea Basin (Lee et al., 2002; Catt, 2007). Clast and palynomorph assemblages support derivation from the Grampian Highlands, Midland Valley and Southern Uplands of Scotland, as well as northern England and the adjacent North Sea. Material diagnostic of the north-west of England, e.g. the Lake District, is not recorded, and curiously, compared to younger

(Devensian) tills, input from the extensive Carboniferous successions of Northumberland and County Durham is minimal (Lee et al., 2002; Davies et al., 2011, 2012).

Initial Late Pleistocene (Devensian) re-advance in County Durham reflects similar erratic transport paths from northern Britain, but with an additional input from north-western England along the Tyne Gap (Davies et al., 2009). This is corroborated by clast fabrics and striae which support west-east ice flow pathways. However, these deposits are immediately overlain by till of exclusively eastern provenance such as the Horden Till (Davies et al., 2009), comprising the characteristic suite of material from the Midland Valley, Southern Uplands, Cheviot Hills and north-eastern England, alongside north-south clast fabric orientations. Further south at Upgang, on the North Yorkshire coast, basal deposits in the Devensian succession reproduce this north-south erratic transport path, again incorporating no material exclusively diagnostic of a Lake District input (Roberts et al., 2013). A striking feature of the Devenisan till successions in both County Durham and North Yorkshire is a notably increased input of low-durability Carboniferous erratic clasts and palynomorphs compared to the pre-Devensian record.

Continuing southwards onto the Holderness coast, recent studies have corroborated the dominance of a north-south ice flow pathway (e.g. Boston et al., 2010; Evans & Thomson, 2010), but lack the quantitative lithological and palynological analysis to facilitate comparison with other erratic transport paths feeding the North Sea Lobe. This study demonstrates that the Skipsea Till at Holderness records incorporation of material from eastern Britain, eroding crystalline and sedimentary substrates from central and southern Scotland, around the Cheviot Hills and southwards through north-east England and the North Sea (Fig. 6). Similarly to the deposits of North Yorkshire and County Durham, the Skipsea Till records an abundance of intact Carboniferous clasts and palynoflora, although is perhaps unique within the Devensian tills for containing reworked Scandinavian erratics. However, with a longer transport path, opportunity to rework erratics from older tills both on and offshore is greatly increased.

5.3. Implications for the evolution of the British North Sea Lobe

Throughout the Mid to Late Pleistocene, till successions in eastern England recorded deposition from a southerly extension of the British-Irish Ice Sheet, sourced to ice dispersal centres in northern Britain. The persistent absence of material derived from north-western Scotland is attributed to a well-established ice divide running broadly N-S across mainland Scotland (e.g. Hughes et al., 2014). Any substrate east of this ice divide was potentially subject to erosion and transport eastwards and southwards towards the North Sea Basin, thus delivering erratic material from the Grampian Highlands, Midland Valley and Southern Uplands to the eastern English coast (this study; Lee et el., 2002; Davies et al., 2009, 2012; Roberts et al., 2013). Further south, ice is diverted along topographical corridors, flowing westwards along the Solway Firth towards the Irish Sea (see Fig. 6), and deflected around the Cheviot Hills to the east along the Tweed Ice Stream (e.g. Livingstone et al., 2012). This dispersal path is supported by the orientation of drumlins and glacial lineations around the Cheviot Massif (e.g. Everest et al., 2005), and clearly represents an important erratic transport path given the recurrent Cheviot input within the Skipsea Till and other deposits of the North Sea Lobe (Lee et al., 2002; Davies et al., 2009, 2011, 2012; Roberts et al., 2013).

During the Mid Pleistocene, west to east erratic transport across northern England appeared inactive, and thus no material from north-western England e.g. the Lake District has been observed within the tills of eastern England (e.g. Lee et al., 2002; Davies et al., 2012). By the Late Pleistocene, however, ice was able to cross the Pennines via the Tyne and Stainmore Gaps, generating west-east oriented streamlined bedforms **(**e.g. Livingstone et al., 2012), and erratic transport pathways which fed Lake District material to ice in eastern Britain (Davies et al., 2009). Expansion of the North Sea Lobe along the eastern English coast during the Last Glacial Maximum effectively blocked trans-Pennine ice dispersal, and thus the termini of these ice streams were dammed to form ice-marginal and proglacial lakes e.g. Glacial Lake Wear, Glacial Lake Pickering and Glacial Lake Humber (Fig. 6; Livingstone et al., 2010; 2012). As a result, erratic transport paths from north-western England were abandoned, and the glacial sediments recorded an exclusively eastern British provenance (e.g. Davies et al., 2009, 2011; Roberts et al., 2013). The Skipsea Till at Holderness recorded the initial southern extension of the North Sea Lobe during the Late Devensian which can be constrained to 21.7-16.2 ka based upon radiocarbon and OSL dating of immediately underlying and overlying deposits (Penny et al., 1969; Bateman et al., 2011). This is further corroborated by high-level lake deposits from palaeo-glacial Lake Humber with an OSL age of 16.6 ± 1.2 ka (Bateman et al., 2008).

This southerly ice flow trajectory, though well constrained by geological evidence, is enigmatic given that the more logical flow path would be for ice from the Midland Valley to have continued eastwards over relatively soft, wet sediments towards the central axis of the North Sea Basin. Significantly, this ice flow trajectory has been interpreted from several different episodes of Mid and Late Pleistocene glaciation (Boulton et al., 1977, 2001; Lee et al., 2002; Clark et al., 2012). Previous studies advocated the onshore (Perrin et al., 1979; Bowen et al., 1986; Fish & Whiteman, 2001) or offshore (Boulton et al., 1991; Davies et al., 2009, 2011; Lee et al., 2012) presence of Fennoscandian ice deflecting British ice along its southwards trajectory. The lack of evidence for Fennoscandian ice within mainland eastern England appears to preclude the 'onshore' scenario; however, its presence and interaction with the central and northern North Sea is likely. For example, Graham et al. (2007) and Bradwell et al. (2008) demonstrated that north-westward overspill of the Norwegian Channel Ice Stream during the Late Weichselian enabled Fennoscandian ice to converge with the British-Irish Ice Sheet to the southwest of Shetland (see Fig. 7a). Such an ice sheet configuration could presumably have also occurred during older glaciations, however, the offshore extent of both British and Fennoscandian ice masses remains largely unknown.

Conversely, Boulton et al. (1977, 1991) and Lee et al. (2002) have proposed models for different Mid and Late Pleistocene glaciations whereby the British-Irish Ice Sheet spread and extended across the floor of the North Sea Basin as a large piedmont lobe (Fig. 7b). The advantage of these models is that they do not necessarily require the interaction of British with Fennoscandian ice, and that ice extent was largely driven by unconstrained flow over a soft and wet deformable substrate (Boulton et al., 1977, 1991; Lee, et al. 2002).

An alternative model was tentatively suggested by Clark et al. (2012), who proposed an ice dome over part of the southern North Sea during the Late Weichselian which caused British North Sea ice to be deflected southwards (Fig. 7c). Whilst such a model cannot be verified by the currently available offshore data (Clark et al., 2012), the concept of a residual dome or particularly a topographical rise (Clark et al., 2012) in the floor of the North Sea is nevertheless worthy of further consideration because of its potential implications for ice dynamics. Such a topographical rise (or a switch to a well-drained substrate) could form a frictional 'sticking-point' causing flow deceleration and ice thickening with enhanced areas of basal sliding being directed into adjacent areas of lower relief and/or poorly-drained substrate. Within the western part of the southern North Sea two obvious 'frictional' areas stand out: firstly, the north-south striking outcrop of Cretaceous Chalk that occurs along the Yorkshire, Lincolnshire and western North Sea margins; and secondly, Dogger Bank, which forms an extensive southwest-northeast trending bathymetric high to the north and northeast

(Fig. 7d). The zone between these two ‘frictional’ areas, and the possible zone of enhanced basal sliding, is characterised by a lower topography, with the geology composed of extensive glacial lacustrine, meltwater and till deposits of Mid and Late Pleistocene age, overlying Mesozoic mudstones (cf. Tappin et al., 2011).

The attraction of the various ice deflection hypotheses lies in the variation of erratic transport paths during evolution of the British-Irish Ice Sheet. It is evident that Mid Pleistocene till successions along the eastern English coast recorded significantly lower populations of Carboniferous erratic material than their Late Pleistocene counterparts (Lee et al., 2002; Davies et al., 2009, 2012; Roberts et al., 2013). This may reflect protection of the Carboniferous substrate during earlier glacial episodes, e.g. by a blanket of older tills, or alternatively enhanced erosion during the Late Pleistocene, potentially driven by switching ice flow pathways. If ice in the North Sea Basin deflected the North Sea Lobe along its more southerly trajectory, the prominent Tweed Ice Stream may have been similarly deflected, arguments for which can be made based on the strike of drumlins and glacial lineations (Raistrick, 1931; Everest et al., 2005; Mitchell, 2008). This is anticipated to have driven greater subglacial erosion and entrainment of widespread Carboniferous bedrock throughout north-east England, due south of the Tweed Ice Stream, as opposed to the considerably younger Mesozoic and Quaternary deposits of the adjacent North Sea.

Currently, it is not possible to test these models further due to the lack of available offshore data, and consequently they remain somewhat speculative. Nor is it currently possible to accurately constrain the extents of the British or Fennoscandian ice sheets, except that previous assertions for the presence of Fennoscandian ice in mainland eastern England during various Mid and Late Pleistocene glaciations are not supported by geological evidence. It is clear from the available geological evidence that the southwards flow of a British North Sea lobe of ice broadly parallel to the trend of the modern coastline of eastern England was a recurrent ice flow pattern, which logically was driven by broadly recurrent glaciological processes and constraints during different Mid to Late Pleistocene glacial events.

6.1. Conclusions

- Re-examination of the lithological and palynological content of the Skipsea Till (Facies E) at Easington, East Yorkshire, confirms that the till was deposited by a lobe of British ice as previously indicated by Catt (2001, 2007). Critical lithological evidence includes: (1) the abundance of locally-derived and far-travelled erratic lithologies and palynomorphs unique to the British geological record including Jurassic Mulgrave Shale Member (“Jet Rock”), Permian Magnesian Limestone, Carboniferous limestone and coal; (2) an extremely low abundance of Scandinavian erratic lithologies (0.28% of the sample population) and a complete absence of characteristic high-grade metamorphic suites; (3) predominance of low-durability sedimentary lithologies (e.g. Jurassic limestone and mudstone, Permian Magnesian limestone) and numerically concentrated Carboniferous palynoflora indicating direct incorporation from bedrock outcrops with minimal reworking.

- Erratic clast lithologies and palynomorphs suggest that ice was ultimately sourced from central Scotland, before flowing through the Southern Uplands and northern England, extending southwards across the floor of the North Sea into eastern England.

- The diverse occurrence of lithologies indicate that during incorporation into this facies of Skipsea Till, most major sedimentary bedrock units in eastern England were largely devoid of Quaternary cover, and were actively eroded subglacially. Studies of other facies of Skipsea Till are currently in progress and will determine whether the focus of subglacial erosion and entrainment shifted either spatially or temporally during emplacement of the till sheet.

- This southwards ice flow trajectory is a recurrent ice flow path that can be replicated from many Mid and Late Pleistocene tills in eastern England including a number that until recently were thought to be of Fennoscandian origin.

- The cause of this southwards ice flow has been debated over several decades and remains ambiguous largely due to the paucity of available offshore evidence. However, the repeated ice flow pattern reconstructed from several different glacial events suggests common and recurrent glaciological constraints within the southern North Sea Basin.

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Figure captions

Fig. 1. Location map of north-west Europe showing the site studied and other locations referred to in the text. Modified from Lee *et al*. (2002) and Woodcock & Strachan (2000). British county boundaries reproduced from Ordnance Survey map data by permission of the Ordnance Survey © Crown copyright 2010.

Fig. 2. Photographs of the sampled section of Skipsea Till at Easington (see Fig. 1). (A) Section profile measures 2.82 m. Box (i) indicates example of sample section cleaned to minimise effect of weathering. (B) Note the poorly sorted nature of the diamicton, and the sub-angular to sub-rounded clast morphologies. Box (ii), re-drawn in (C), highlights the glacially striated chalk clast recovered from the till.

Fig. 3. Population and lithostratigraphical association of 8-16 and >16mm clast assemblages within each sample of the Skipsea Till studied.

Fig. 4. Carboniferous allochthonous palynomorphs extracted from two sub-samples of the Skipsea Till. A-D) *Densosporites* spp.; E-H) *Lycospora* spp.; I) *Tripartites* spp.; J) *Endosporites globiformis*; and K) *Tripartites vetustus*. The scale bar measures 10 μm.

Fig. 5. Bedrock geology map of northern Britain showing outcrop occurrences of lithostratigraphical groups found within the Skipsea Till erratic clast and palynomorph assemblages. A-J indicate geographical regions referred to in the text. Map modified from BGS DiGMapGB-625. Reproduced with permission of the British Geological Survey © NERC. All rights reserved.

Fig. 6. Proposed ice flow path for the British-Irish Ice Sheet that deposited the Skipsea Till, overlain onto outline bedrock geological boundaries (i), with corresponding bedrock geology map and key inset (ii; see Fig. 5). Palaeo-ice marginal lakes and bedforms associated with advance of the North Sea Lobe modified after the Britice Glacial Map of Britain (Clark et al. 2004). Geological map adapted from BGS DiGMapGB-625. Reproduced with permission of the British Geological Survey © NERC. All rights reserved.

Fig. 7. Hypothetical models for ice flow within the North Sea Basin to account for the development of the southward-flowing North Sea lobe. (A) Southwards deflection of the North Sea lobe (NSL) by Baltic ice (BI) and the overspill of the Norwegian Channel Ice Stream (NCIS) (cf. Fish and Whiteman, 2001); (B) Piedmont-style lobe of British ice without necessary interaction with Fennoscandian ice (cf. Boulton et al., 1977, 2001; Lee et al., 2002); (C) Southern flow path of North Sea lobe driven by the development of an ice dome in the North Sea Basin (cf. Clark et al., 2012); (D) Southern flow path of North Sea lobe driven by elevated or free-draining sticking-points within the subglacial bed (this study).

Table 1. Lithostratigraphical association of the 8-16 mm and >16 mm erratic clast assemblages extracted from the Skipsea Till.

Table 2. The distribution of palynomorphs in the two samples studied in eight age-related groups. The numbers indicate the absolute numbers of palynomorphs in the grain count. An “X” indicates that the respective palynomorph is present, but was not encountered in the count. An ellipsis (...) indicates that the respective palynomorph is not represented. Full author citations are included for the taxa at and below species level.

Table

Age	Lithology	8-16mm (n=661)	>16mm (n=56)	Total
Allochthonous sedimentary		n	n	%
Total Pleistocene		*68*	*5*	*10.32*
	Quartzite	32	2	
	Weathered Flint	32	1	
	Greensand chert	4	1	
	Glauconitic sandstone	0	1	
Total Cretaceous		*198*	*22*	*30.68*
	Chalk, fresh flint	198	22	
Total Jurassic		*65*	*5*	*9.76*
	Grey/brown calcareous sandstone, grey-green micaceous limestone	27	3	
	Grey micaceous mudstone, black bituminous mudstone	15	0	
	Ferruginous sandstone, mudstone, ironstone	9	0	
	Shelly +/ oolitic limestone, shell material, *Rhaxella* chert	14	2	
Total Permo-Triassic		*85*	*7*	*12.83*
	Magnesian Limestone, crystalline dolostone, dolomitic sandstone	75	6	
	New Red Sandstone, wind-faceted sandstone (*dreikanter*)	3	0	
	Evaporitic sandstone/limestone, gypsum	7	1	
Total Carboniferous		*93*	*3*	*13.39*
	Quartzo-feldspathic, micaceous, calcareous organic-rich sandstone	55	1	
	Pink-red crystalline limestone	7	0	
	Dark grey-brown crystalline, crinoidal +/ shelly limestone	29	2	
	Coal, fossil material	2	0	
Total Devonian		*13*	*1*	*1.95*
	Old Red Sandstone	13	1	
Total Lower Palaeozoic		*16*	*0*	*2.23*
	Greywacke	10	0	
	Dark green chert	6	0	
Total unknown provenance		*36*	*3*	*5.30*
	Quartzo-feldspathic, polylithic, micaceous sandstone	35	3	
	Green mudstone	3	0	
Allochthonous crystalline				
Total Permian		*0*	*2*	*0.28*
	Microgranite	0	1	
	Rhomb porphyry	0	1	
Total Carboniferous		*24*	*6*	*4.18*
	Mafic quartz +/ olivine porphyry, basalt	11	2	
	Dolerite (+/ Tertiary?)	12	3	
	Trachyte	1	1	
Total Devonian		*60*	*2*	*8.65*
	Rhyolite porphyry, andesite porphyry, andesite, felsite	31	0	
	Granite, microgranite, granodiorite	24	1	
	Volcaniclastic sediment, red jasper	2	0	
	Quartzose schist, metapsammite	3	1	
Total unknown provenance		*3*	*0*	*0.42*
	Fine grained intermediate igneous with feldspathic phenocrysts	1	0	
	Ferruginous mafic-intermediate igneous	1	0	
	Grey-blue intermediate igneous with red crystals	1	0	

Table

Palynomorphs	*Sample 1 (n)*	*Sample 2 (n)*
Carboniferous pollen and spores		
Carboniferous spores - indeterminate	23	11
Cirratriradites saturni (Ibrahim 1932) Schopf et al. 1944	X	X
Densosporites spp.	45	26
Endosporites globiformis (Ibrahim 1932) Schopf et al. 1944	1	…
Florinites spp.	…	1
Lycospora pusilla (Ibrahim 1932) Schopf et al. 1944	104	82
Radiizonates sp.	1	X
Reticulatisporites spp.	2	?X
Simozonotriletes intortus (Waltz 1938) Potonie & Kremp 1954	…	X
Tripartites vetustus Schemel 1950	X	X
Total Carboniferous palynomorphs	**176**	**120**
Jurassic pollen spores		
Callialasporites spp.	15	3
Cerebropollenites macroverrucosus (Thiergart 1949) Schulz 1967	…	X
Chasmatosporites spp.	1	1
Classopollis classoides (Pflug 1953) Pocock & Jansonius 1961	10	15
Classopollis meyeriana Klaus 1960	2	1
Dictyophyllidites sp.	1	9
Ischyosporites variegatus (Couper 1958) Schulz 1967	…	X
Perinopollenites elatoides Couper 1958	4	X
Jurassic marine microplankton		
Gonyaulacysta jurassica (Deflandre 1939) Norris & Sarjeant 1965 subsp. *adecta* Sarjeant 1982	X	…
Halosphaeropsis liassica Mädler 1963	2	3
Hystrichosphaera orbifera (Klement 1960) Stover & Evitt 1978	X	…
Liasidium variabile Drugg 1978	1	1
Nannoceratopsis deflandrei Evitt 1961 subsp. *senex* (van Helden 1977) Ilyina in Ilyina et al. 1994	X	1
Nannoceratopsis gracilis Alberti 1961	X	…
Oligosphaeridium patulum Riding & Thomas 1988	…	1
Pareodinia sp.	1	1
Perisseiasphaeridium pannosum Davey & Williams 1966	…	X
Systematophora sp.	…	X
Total Jurassic palynomorphs	***37***	***36***
Cretaceous spore		
Cicatricosisporites sp.	X	X
Cretaceous dinoflagellate cysts		
?*Isabelidinium* sp.	X	1
Cribroperidinium spp.	1	5
Hystrichodinium voigtii (Alberti 1961) Davey 1974	…	X
Hystrichodinium spp.	X	…
Odontochitina operculata (Wetzel 1933) Deflandre & Cookson 1955	X	…
Oligosphaeridium complex (White 1842) Davey & Williams 1966	…	X
?*Phoberocysta* sp.	X	…
Wallodinium cylindricum (Habib 1970) Duxbury 1983	…	X
Total Cretaceous palynomorphs	**1**	**6**
Quaternary pollen		

Pinus	7	6
Quaternary pollen - indeterminate	2	X
Tilia	…	X
Quaternary dinoflagellate cysts		
Achomosphaera andalousiensis Jan du Chêne 1977	1	…
Operculodinium centrocarpum (Deflandre & Cookson 1955) Wall 1967	…	?1
Quaternary dinoflagellate cysts - indeterminate	2	6
Spiniferites spp.	11	2
Total Quaternary palynomorphs	**23**	**15**
Non-age diagnostic palynomorphs		
Botryococcus braunii Kützing 1849	0	1
chorate dinoflagellate cysts - indeterminate	0	1
dinoflagellate cysts - indeterminate	11	2
Micrhystridium spp.	12	3
Pediastrum spp.	1	1
prasinophytes	31	0
pre-Quaternary bisaccate pollen	2	0
smooth trilete spores	3	1
Total non-age diagnostic palynomorphs	**62**	**95**
Total	**299**	**272**

Figure

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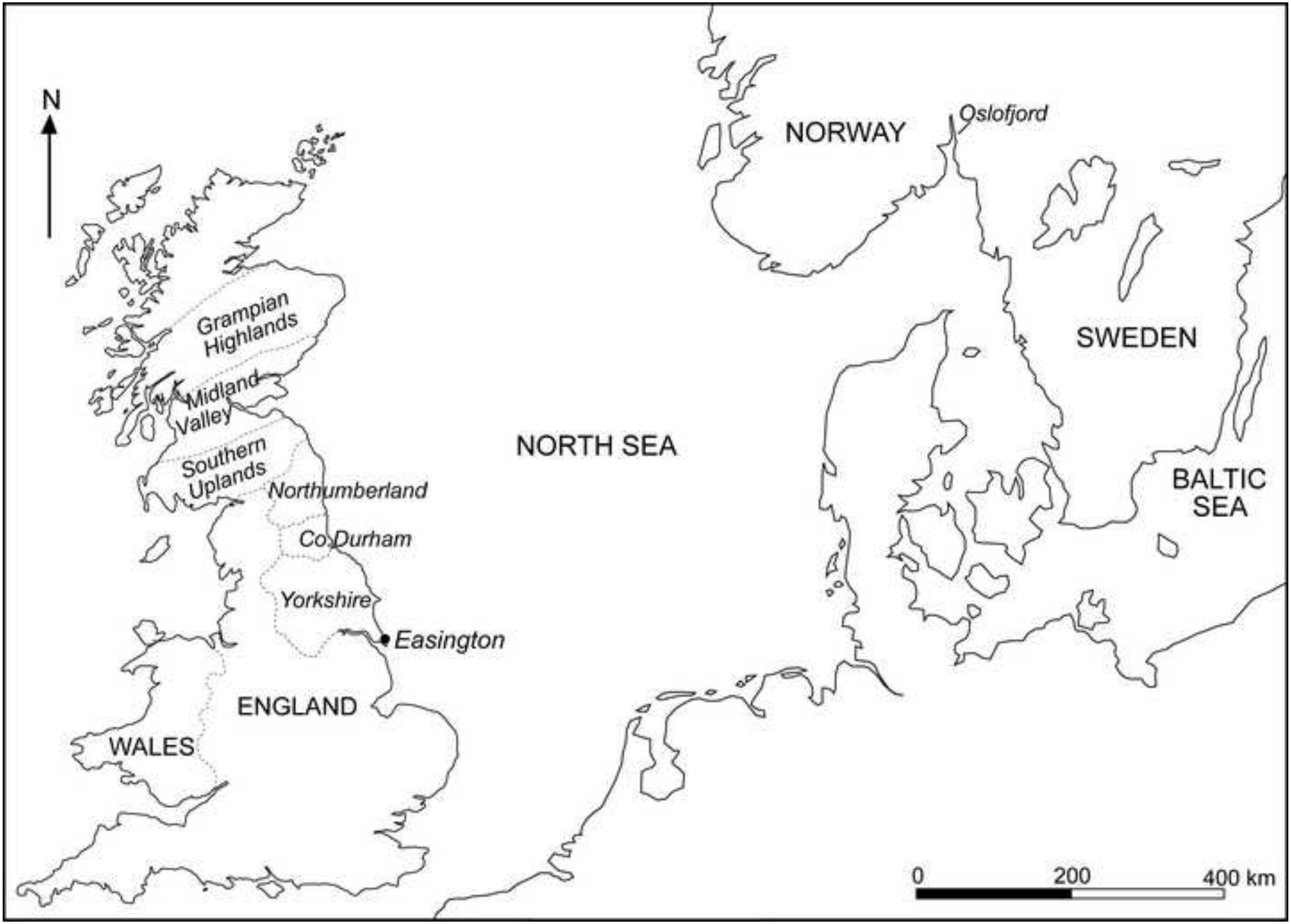

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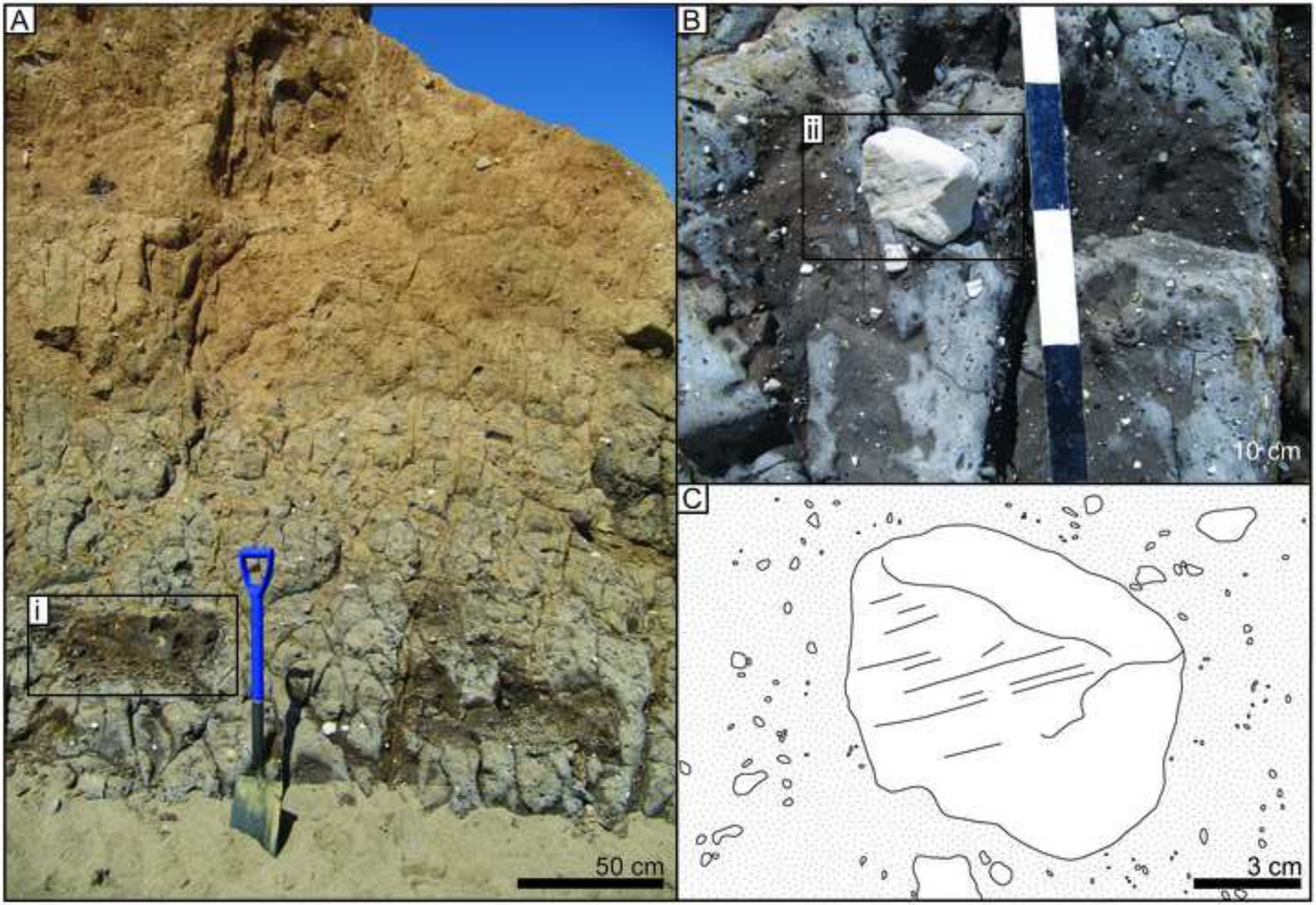

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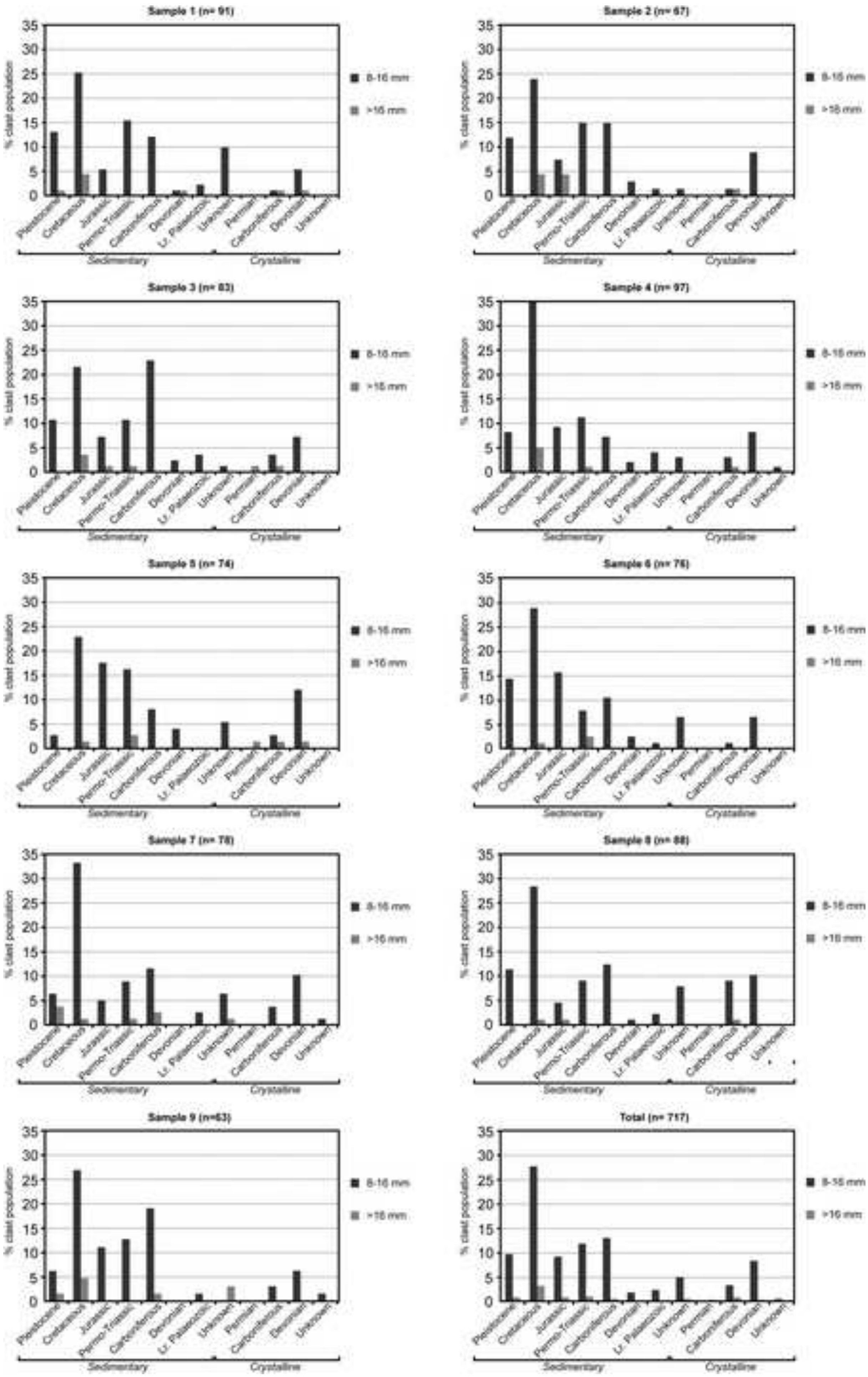

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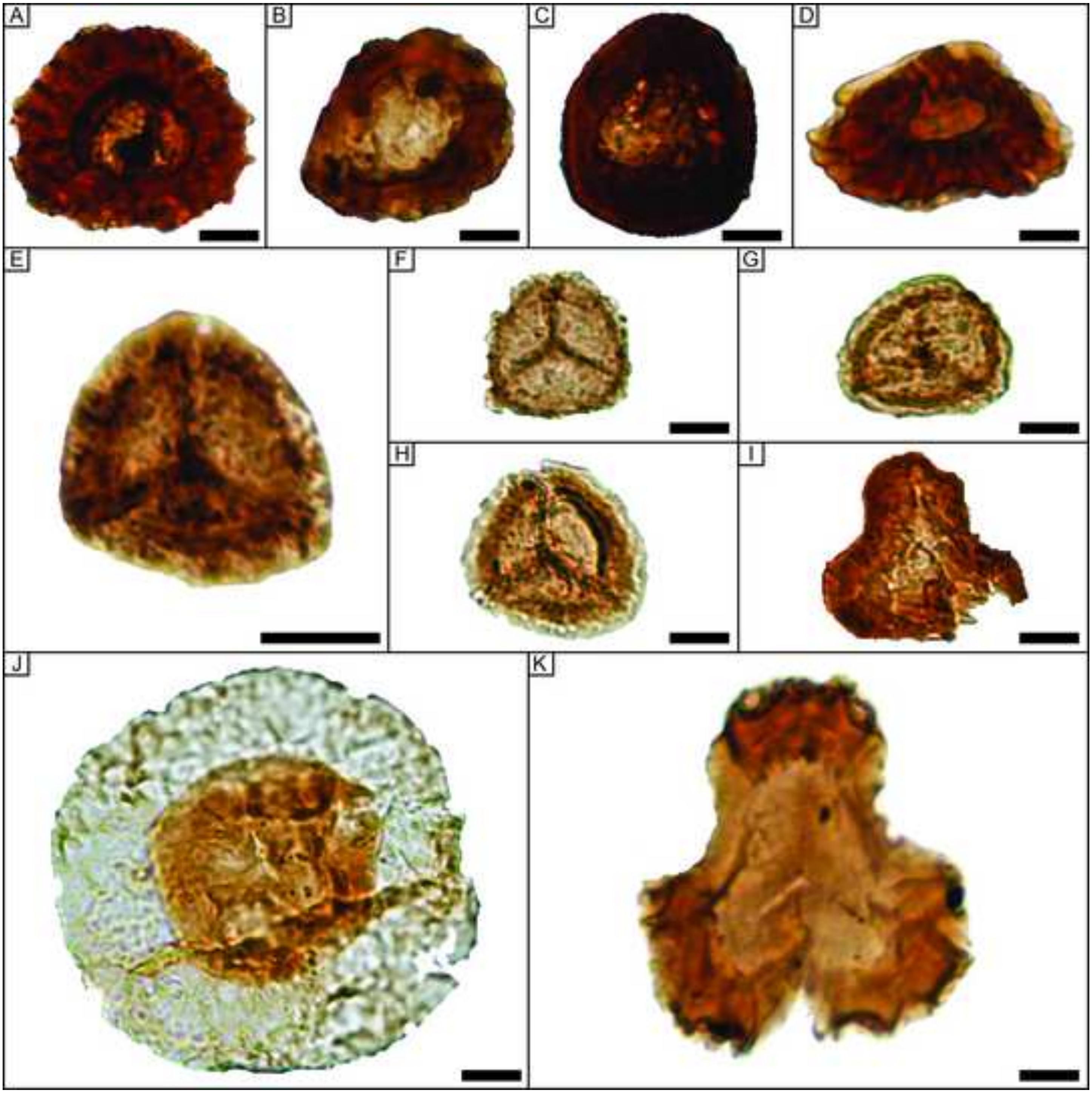

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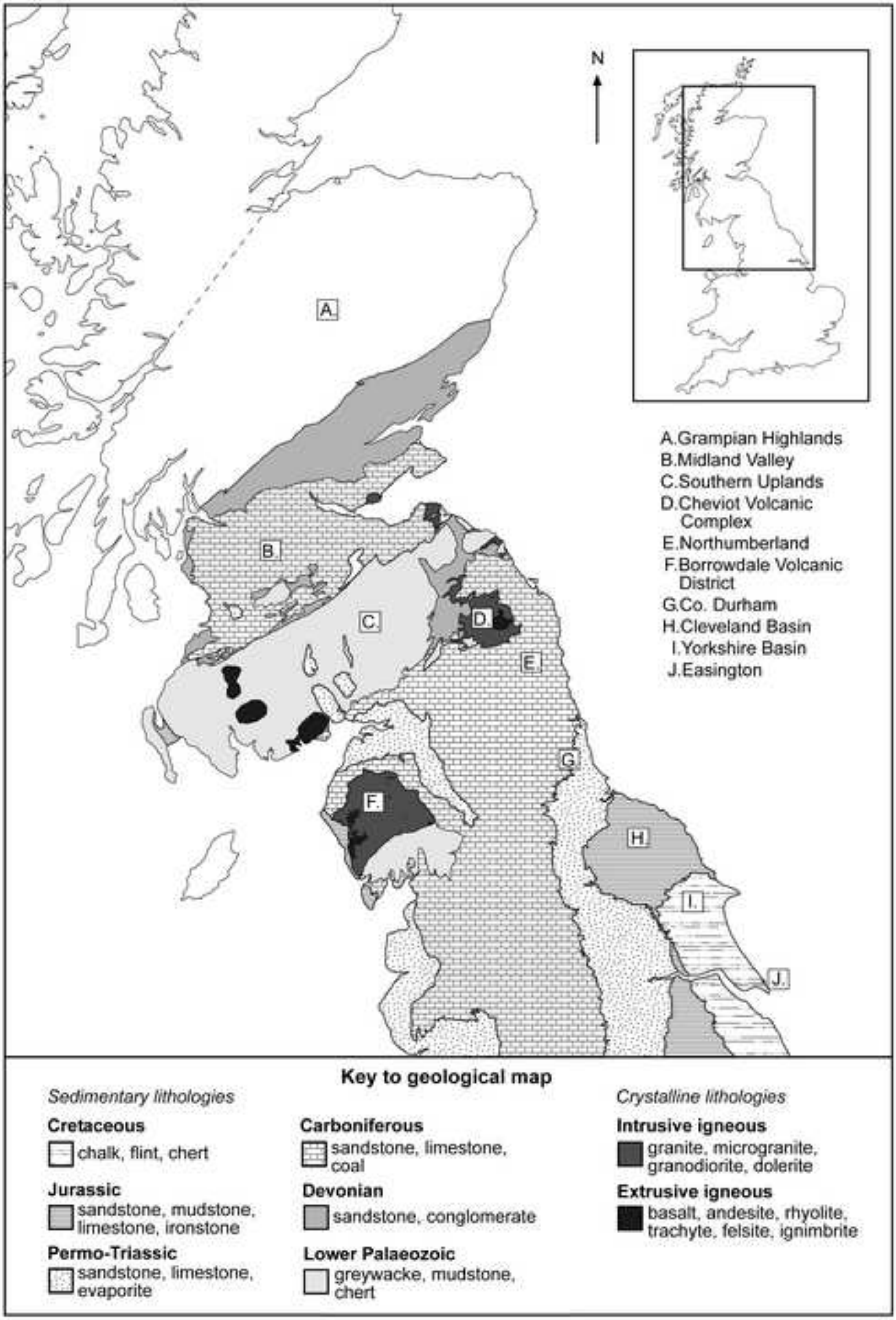

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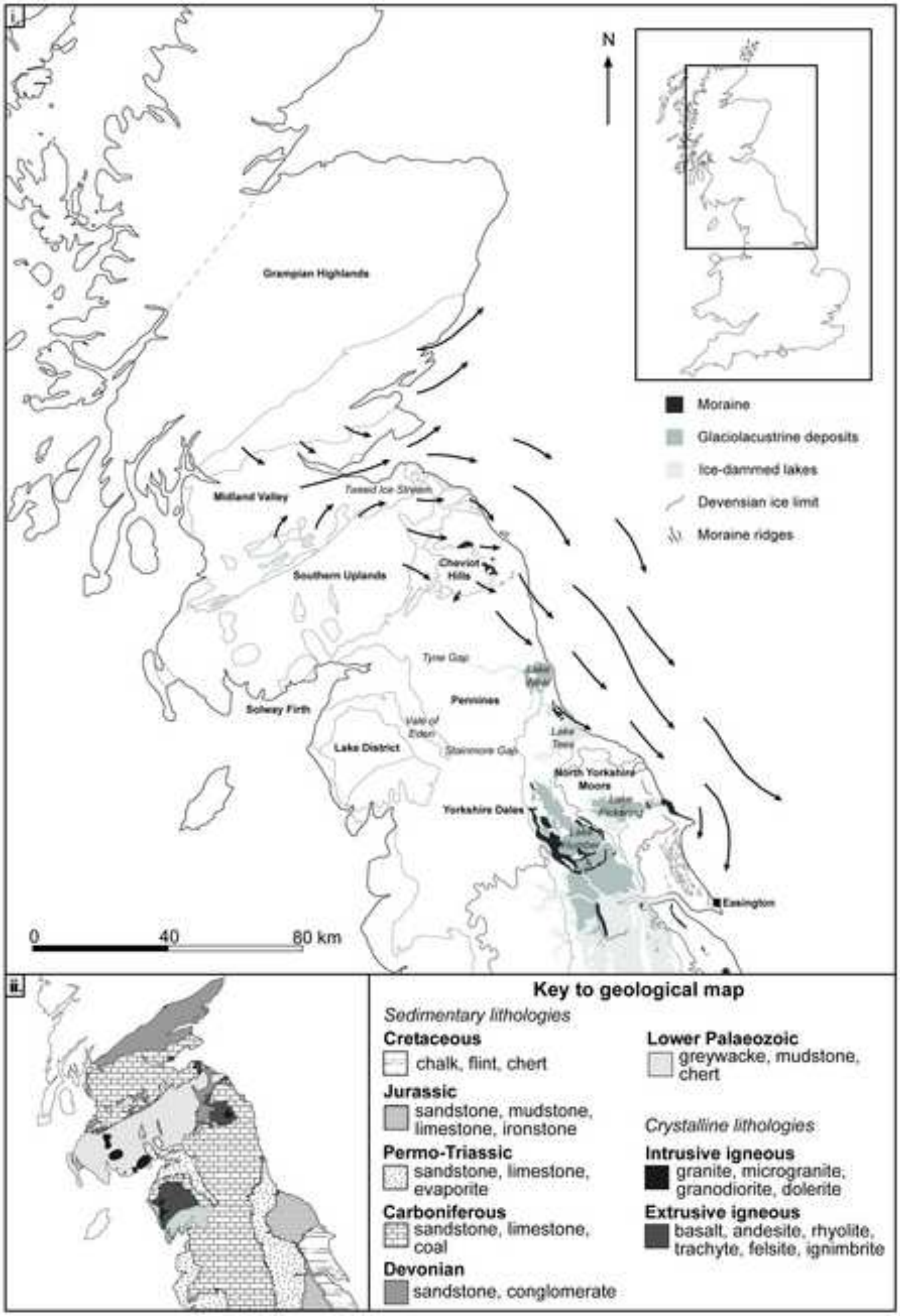

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